The Effects of Proton Irradiation on the Performance of mm-wave Transmission Lines Implemented in SiGe Technology

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Abstract— **This paper examines, for the first time, the effects of radiation on transmission lines implemented in a commercial SiGe HBT BiCMOS technology. Two different types of mm-wave transmission lines were designed, fabricated, and measured up to 110 GHz, and irradiated with 63.3 MeV protons to fluences as high as 5×10^{13} p/cm^2. The results demonstrate that radiation-induced changes are minimal in such lines, making them potentially suitable for use in space-based SiGe monolithic mm-wave communications systems.**

Index Terms: SiGe, HBT, mm-wave, transmission lines, TFMS, CPW.

I. Introduction

As few as ten years ago, studies of transmission lines in conventional silicon integrated circuit (IC) technology were virtually non-existent due to the poor intrinsic performance of the requisite transistor building blocks. This scenario has changed radically, however, with the emergence of bandgap-engineered SiGe HBT technology as a viable competitor in the microwave and mm-wave applications arena. Today, SiGe HBTs with peak f_T/f_{max} values above 200 GHz exist in commercial foundries, and record values of f_T/f_{max} above 300 GHz have been reported [1], making the emergence of viable, low-cost, integrated microwave and mm-wave systems up to 100 GHz using conventional Si IC manufacturing a real possibility. An important potential application of such millimeter-wave IC technologies lies in very high bandwidth ($>$ 1 Gb/sec) point-to-point, communications data links, for both commercial and defense-based needs. Given the inherent total-dose tolerance (to multi-Mrad levels) of SiGe HBT technology, its potential application in mm-wave space electronics systems has generated significant recent attention [2].

Clearly, the eventual success of such mm-wave systems requires not only active components (i.e., transistors), but also schemes for the on-chip interconnection of the active circuitry at very high frequencies. One such potential interconnect solution is to use a co-planar waveguide (CPW) structure on high resistivity silicon, as was reported in [3]. Such a substrate, however, is not traditionally available in commercially-available (low-cost) SiGe processes, and if it is, comes only at an undesirable cost penalty. An alternate potential transmission line configuration is that of the Thin Film Microstrip (TFMS), and is investigated in this work. Such a configuration was explored in [4]; however, the use of polymide dielectrics are also not commercially available as a dielectric in foundry processes and are thus undesirable from a cost perspective. Given the requirement of thick layers of dielectric (typically $> 5\mu$m or more) in any mm-wave transmission line implementation, their performance in an ionizing radiation environment would seem questionable, at best, and has not to date been investigated.

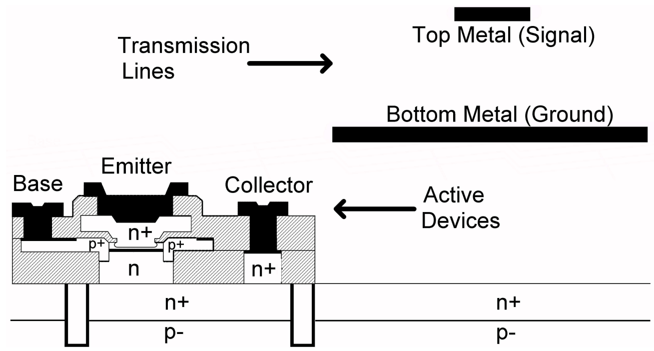

Fig. 1. Representative cross-section of the SiGe HBTs and transmission lines. Drawing is not to scale.

In a standard SiGe process technology, the signal line and the ground can be selected as the topmost and lowest routing metal layers available in the process, respectively, as can be seen in Fig. 1. In this paper, we fabricated and measured TFMS lines using the Samsung Electronics SiGe HBT BiCMOS process, without additional post-fabrication processing, and while maintaining strict adherence to the IC design rules. Such lines required slotted ground planes to meet the design rule criteria. The resulting variations between this ground plane and a solid ground plane are simulated and presented. Additional work [5], [6], and [7], also explored the use of commercially available processes, but only provided measured data up to

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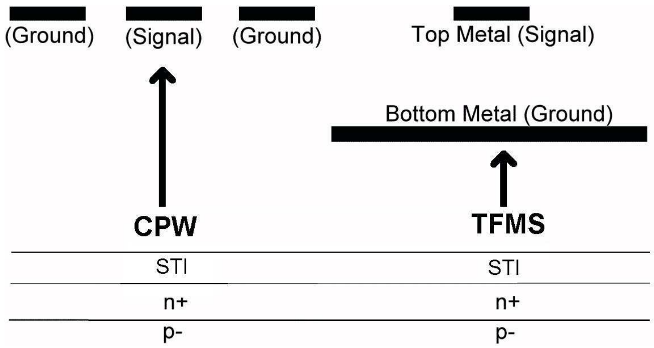

Fig. 2. Representation of Coplanar Waveguide (CPW) and Thin Film Microstrip (TFMS) transmission line configurations.

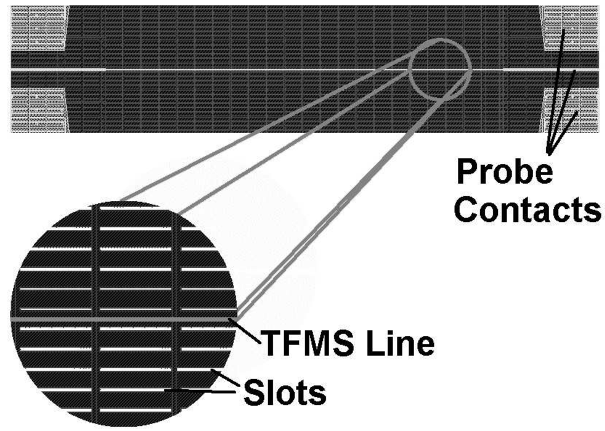

Fig. 3. Layout of the transmission lines with the inset showing the ground plane slots.

a maximum of 40 GHz, and therefore too low in frequency for many of the mm-wave communications applications. The radiation response of these transmission lines is presented as a function of proton fluence, for the first time, up to 110 GHz.

II. Transmission Line Design and Experiment

The two different types of transmission lines fabricated were: 1) Coplanar Waveguide (CPW), and 2) Thin Film Microstrip (TFMS) lines. The different geometries of these lines are shown in Fig. 2. The CPW lines were constructed on the top layer of metal and can be probed directly on this layer. The fields within the lines are exposed to the Si substrate below without shielding. The TFMS lines were constructed with the top layer of metal acting as the signal trace, and the bottom layer acting as the signal ground. The ground also acts as a shield from the substrate. The TFMS lines were designed to provide a nominal 50 Ω characteristic impedance on the 4 layer metal process from the commercial SiGe HBT BiCMOS process used. Process design rules mandated that wide metal traces, such as those required in the ground plane, have periodic "slots" placed in them for layer planarity and processing integrity. Thus, slots were placed in the ground plane with dimensions of 10 μm x 90 μm with metal runs of 20 μm in between, as can be seen in Fig. 3. Due to the narrow separation between the signal and ground traces, nominally 3.24 μm, a very narrow line width of 7.0 μm wide had to be used for the signal trace. The CPW lines were probed directly by simply opening the passivation above the lines. The TFMS lines were transitioned to a grounded CPW structure through a taper to facilitate on-wafer probing.

Characterization of the lines was performed from 10 to 110 GHz using an Agilent 8510 vector network analyzer. Line loss was calculated through the use of Thru-Reflect-Line (TRL) structures which were placed on the wafer (see Fig. 4). These structures consisted of an "open" and a "thru" of the CPW with a taper structure, as well as line lengths of 550, 1100, 2200, and 4400 μm. The deembedding software used was the MULTICAL [8] software provided by NIST. This software allowed for reflections and losses of the transitioning CPW structures to be calibrated out, leaving only the TFMS signal trace. Similar structures were used for the CPW lines. As with

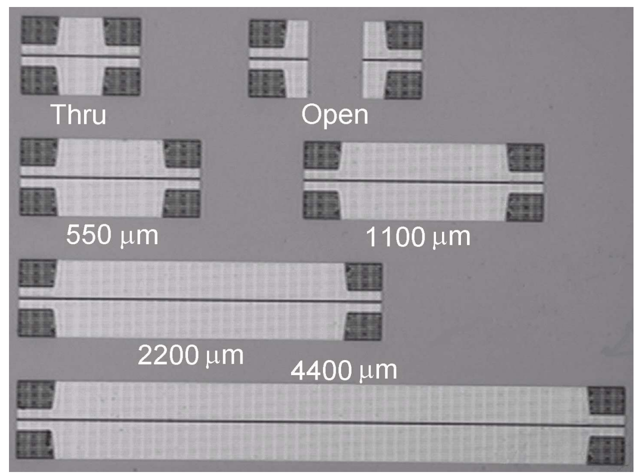

Fig. 4. Die photo of the on-wafer TRL structures of the TFMS lines.

the TFMS lines, the probe landing transitions on the CPW lines were also calibrated out to simply leave the transmission lines themselves for measurement.

The samples were first comprehensively characterized to 110 GHz, and subsequently irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) located several meters upstream of the target establishes a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 20 nA to 100 nA allow testing with proton fluxes from 1.0×10^9 to 1.0×10^{12} protons/cm^{2}sec. The dosimetry system has been previously described [9] [10], and is accurate to about 10%. At a proton fluence 5.0×10^{13} p/cm^2, the measured equivalent gamma dose was approximately 6,759 krad(Si). Because of the need for post-irradiation on-wafer probing, the samples were irradiated with all terminals floating. This is not believed to have any significant impact on the results, primarily due to the fact that these structures are purely passive.

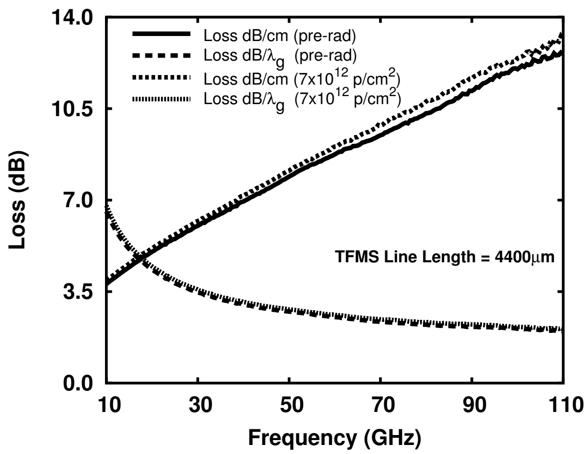

Fig. 5. Measured attenuation of the microstrip line in dB/cm and dB/λ_g at a fluence of 7×10^{12} p/cm^2.

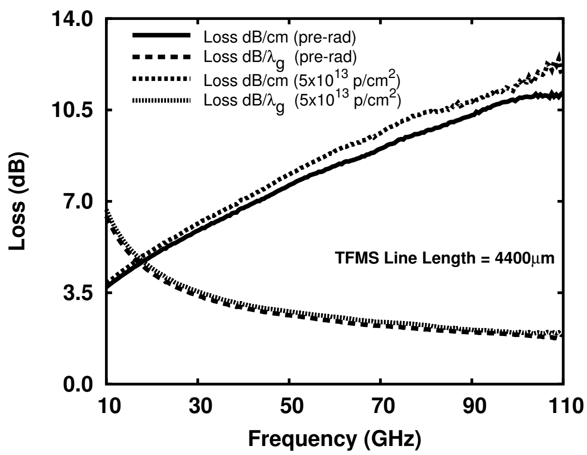

Fig. 6. Measured attenuation of the microstrip line in dB/cm and dB/λ_g at a fluence of 5×10^{13} p/cm^2.

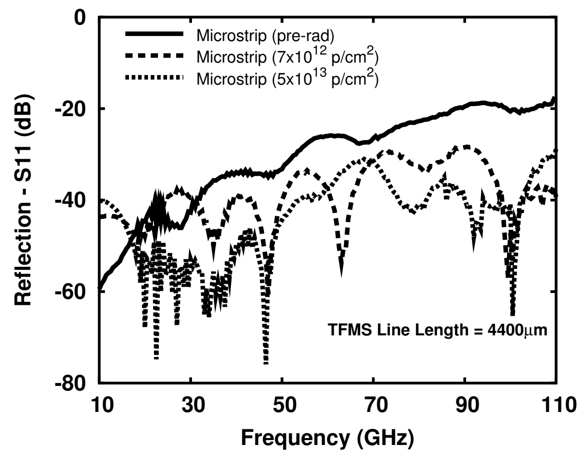

Fig. 7. Measured reflection of microstrip pre- and post-radiation.

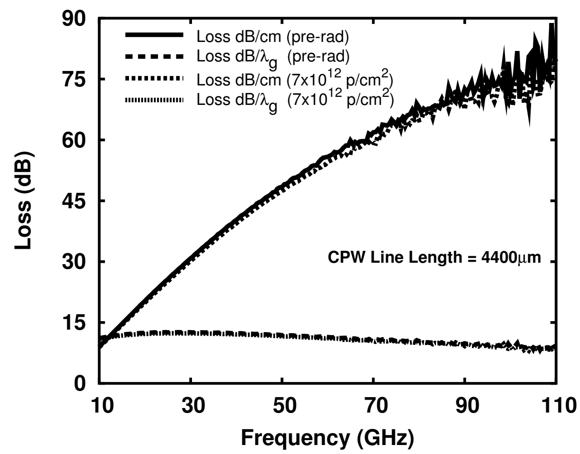

Fig. 8. Measured attenuation of the CPW line in dB/cm and dB/λ_g at a fluence of 7×10^{12} p/cm^2.

III. Discussion

The measured loss of the TMFS lines, before and after proton exposures of 7×10^{12} protons/cm^2 and 5×10^{13} protons/cm^2 are shown, respectively, in Fig. 5 and Fig. 6. The loss is given in dB/cm as well as dB/λ_g (loss per guided wavelength). The measured reflection coefficient, $|S11|$, shown in Fig. 7, shows that both before and after irradiation the transmission lines were extremely well-matched to 50 Ω. While the loss per unit length is fairly high for the mm-wave frequency bands of immediate interest for integration of transmission lines in SiGe technology, the loss per guided wavelength remains practical for typical high-frequency designs. In addition, their integration in SiGe technology would also allow for transistor amplification to overcome this inherent loss. The variation in loss both before and after irradiation is negligible, especially if considered in the case of loss per guided wavelength. By referring to $|S11|$ both before and after irradiation, it can also be seen that radiation does not affect the characteristic impedance of the TFMS lines, which is clearly important.

The measured loss characteristics of the CPW transmission lines, both before and after irradiation, are shown in Fig. 8 and Fig. 9. Unlike for the TFMS lines, the CPW structures show significant loss and hence little promise in this commercial SiGe process for practical mm-wave circuit designs. This large loss is due primarily to the low resistivity silicon used as the substrate material. This causes non-symmetrical fields seen above and below the CPW structure and also induces parasitic microstrip modes. A conductor-backed CPW architecture would reduce these two effects, but is not an option in this case, as the thin 3.24 μm oxide layer separating the metal layers would require an extremely narrow center conductor to keep the microstrip mode from dominating the performance, resulting in very large losses. Even though the usefulness of these CPW lines is impractical, it can nevertheless be seen that the change in loss of the lines after irradiation is again minimal. Similar to the behavior observed for the TFMS lines, the change in $|S11|$, and ultimately the change in line impedance, is also not affected by radiation, as can be seen in Fig. 10.

The net effect of proton exposure on the TFMS lines as a

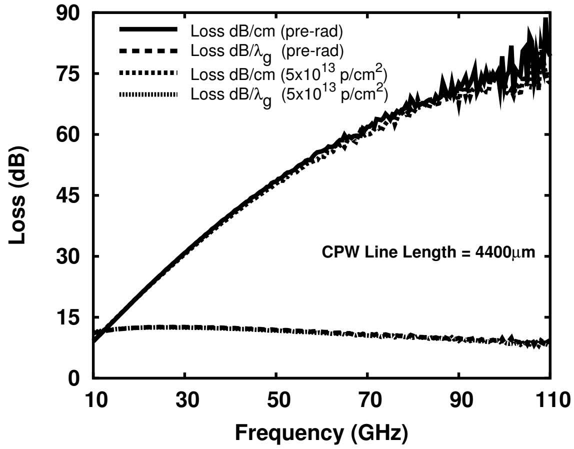

Fig. 9. Measured attenuation of the CPW line in dB/cm and dB/λ_g at a fluence of 5×10^{13} p/cm^2.

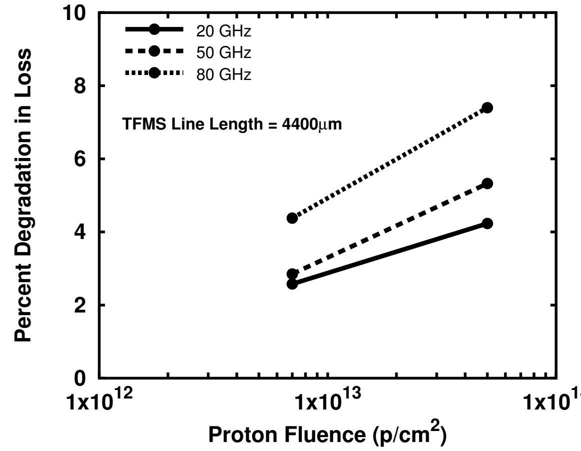

Fig. 11. Percent change from pre-radiation loss as a function of fluence and frequency for TFMS lines.

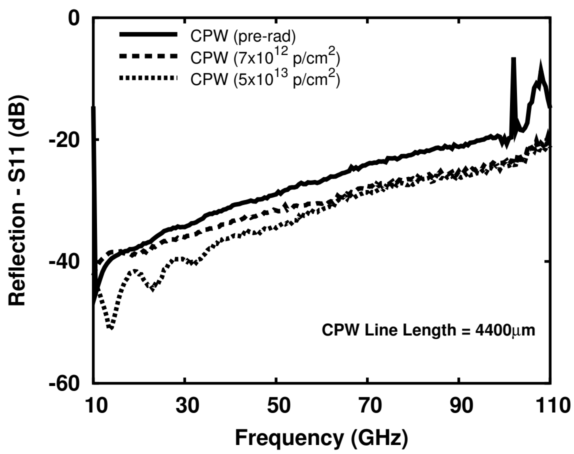

Fig. 10. Measured reflection of the CPW line both before and after irradiation.

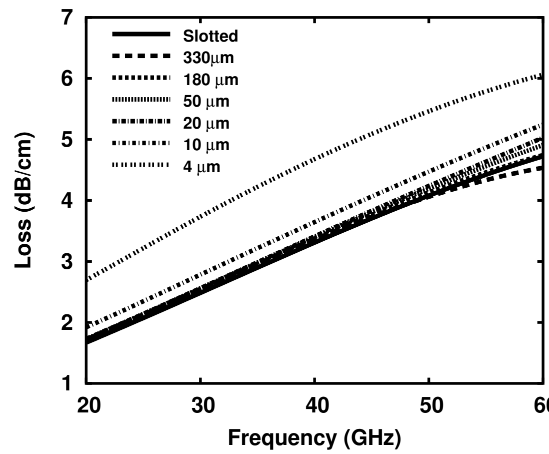

Fig. 12. Simulated loss characteristics as a function of ground plane width for TFMS lines.

function of frequency and fluence are shown in Fig. 11. Even though an upward trend (degradation in loss) with increasing proton fluence can be clearly observed, the nominal loss at 50 GHz is only 4%, which should have minimal impact on circuit and system design. Furthermore, the plot suggests, through extrapolation to decreasing radiation levels, that there is potentially a radiation threshold below which no degradation in line loss occurs over all frequencies to 110 GHz. More data at intermediate fluences will be required to confirm this.

The TFMS lines were designed such that the slotted ground plane extended to the edges of the CPW probable pads after the transition from the center conductor. This distance was over 200 μm in each direction from the center conductor, yielding, in essence, an infinite ground plane. Since such a ground plane would not be employed in any real designs, due to size constraints, TFMS lines with narrower ground planes were also simulated. Fig. 12 shows the simulated loss characteristics for lines with a similar geometry to that which was fabricated. The total width of the ground plane under the conductor was varied during simulation. A general rule-of-thumb is that the ground plane should extend at least 3 times the distance between the ground plane and the signal conductor. For TFMS lines with an oxide layer separation of 3.24 μm, this would suggest a ground plane of 25 μm width. This estimate is confirmed by results in Fig. 12, where it is seen that any solid ground plane greater than or equal to 20 μm in width experiences similar values of loss as does the simulated slotted ground plane used in the experiment. This suggests that the measured results are a good representation of what would ultimately be seen with finite ground planes used in real mm-wave circuit and system design.

IV. Summary

We have presented pre- and post-radiation measurements to 110 GHz of CPW and TFMS transmission lines implemented in a commercial SiGe HBT BiCMOS technology. Due to the requisite low substrate resistivity in this SiGe technology, it is clear that unshielded CPW lines are not a viable design point for microwave and mm-wave applications. The TFMS approach, however, shows potential, especially in light of their inherent radiation tolerance. Consequently, the feasibility of using TFMS lines in high-frequency space communications applications fabricated in a SiGe technology platform up to mm-wave frequencies has been demonstrated for the first time.

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